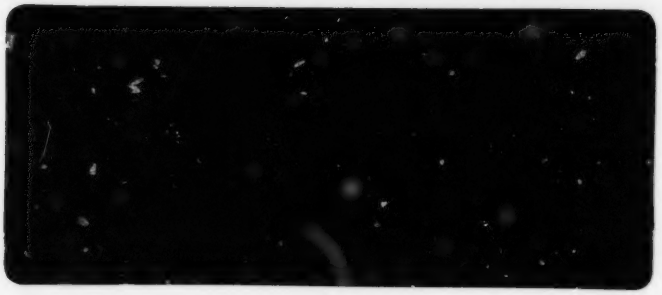
Report Rapport

Atomic Energy Control Board

Commission de contrôle de l'énergie atomique



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EROSION OF SURFACE AND NEAR SURFACE DISPOSAL FACILITIES

by

MacLaren Plansearch Inc.

A research report prepared for the
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Research report

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EROSION OF SURFACE AND NEAR-SURFACE DISPOSAL FACILITIES

A literature review prepared by MacLaren Plansearch Inc. under contract to the Atomic Energy Control Board.

ABSTRACT

A literature search was undertaken to identify existing data and analytical procedures regarding the processes of gully erosion. The applicability of the available information to the problems of gully erosion potential at surface and near surface disposal sites is evaluated. It is concluded that the existing knowledge regarding gully erosion is insufficient to develop procedures to ensure the long-term stability of disposal sites. Recommendations for further research are presented.

RÉSUMÉ

Un examen de la documentation a été effectué pour identifier les données actuelles et les méthodes analytiques concernant les processus d'érosion des ravins.

L'application des informations disponibles aux problèmes potentiels de l'érosion des ravins affectant des sites d'enfouissement à la surface ou près de la surface a été évaluée. Il a été conclu que les connaissances actuelles sont insuffisantes pour développer des méthodes qui assureront une stabilité à long terme des sites d'enfouissement.

Le rapport recommande divers travaux additionnels de recherche.

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1. Introduction

The processes and rates of soil removal by sheet erosion are relatively well defined and understood. This type of erosion poses little hazard to disposal sites since it occurs uniformly and at a slow rate. However, under certain conditions, non-uniform localized and rapid erosion may occur in the form of gullying. This type of erosion may cause the sudden breach of the ground surface, exposing waste to subsequent transport and redistribution.

The initiation and rate of gully erosion is the result of the complex inter-relationship of many factors which are not always easy to control. The purpose of this study is to review the state-of-the-art in the understanding of gully erosion processes and methods of analysing and controlling the growth of gullies with respect to the problems of disposal sites.

The specific tasks to be performed, as outlined in the Terms of Reference were:

A) Search for and compile all information on:

1) conditions that favour or lead to gully erosion, and other forms of non-uniform erosion, of unconsolidated materials which may affect the capability of a disposal facility to contain and isolate wastes. In so doing address the following:

a) the types of materials subject to erosion, such as naturally occurring materials in which a facility may be constructed, materials used for engineered covers or liners of a facility and materials which may be placed in a disposal facility, including fill;

b) the nature of the materials in subtask a), such as lateral and vertical variations in composition, texture, moisture content, degree of lithification, and thickness, as well as engineering parameters (such as Atterburg limits) at any given location;

c) climatic conditions and seasonal variations, including regular processes and episodic events;

d) topography;

e) vegetation;

f) other factors affecting non-uniform erosion.

2) Data related to the quantification and determination of the magnitude of conditions and factors identified in Task 1.

3) The kinds of measurements made to evaluate the amount, rate, and duration of erosion, given the conditions in Task 1 and the information requirements of Task 2.

4) Case histories with sample data, interpretations, evaluations and predictions of gully erosion and other non-uniform mechanisms of erosion.

B) Evaluate the adequacy and completeness of the theories, interpretations and data in Task A in order to determine:

1) what measurements are needed to collect the data to characterize gully and other non-uniform erosion mechanisms at a site.

2) methods of evaluating the extent and rates of erosion at a site.

C) Write a report in which the information gathered for Tasks A and B is clearly and concisely presented in the context of Canadian conditions. Original interpretations derived from this study must also be included.

The following sections prsent the results, conclusions and recommendations of the study.

2. Method of Information Search

Two basic methods were employed: a computerized search of technical data bases and direct personal contacts with known researchers in the field. the computerized data base search was conducted in two stages. In the first stage, all articles having the following combination of keywords were requested: GULL? or RILL? and EROS? or EROD? Nine data bases were considered and only the titles of the articles were requested. The results are shown in Table 1.

In the second stage, the titles were screened and many were eliminated because of one of the following:

(i) non-relevance to the study objectives
(ii) different language other than English or French
(iii) repetition

Full information on the remaining articles (165 articles), including the abstracts was obtained and stored in our computer system.

The abstract list was then reviewed by the study team. The list was screened, and some articles were eliminated, based on the same criteria as mentioned above. The remaining articles were then listed to form a preliminary bibliography and requests were sent out to obtain full copies of these articles. A total of 36 papers and publications have been reviewed in full to date.

TABLE 1

RESULTS OF COMPUTERIZED DATA BASE SEARCH

	Data Base Name	Period Covered	Number of Citations
1.	GEOREF (American Geological Institute)	1785 - 1986	403
2.	CAB Abstracts (Commonwealth Agricultural Bureau)	1984 - 1986 1972 - 1983	132 329
3.	COMPENDEX (Engineering Index)	1970 - 1986	110
4.	EI Engineering Meetings	- 1986	59
5.	CRIS USDA (U.S. Dept. of Agricultural Projects)	1975 - 1986	48
6.	AGRIS International (from UN FAO)	1974 - 1986	29
7.	AGRICOLA (U.S. National Agricultural Library)	1979 - 1986 1970 - 1978	161 64
8.	Water Resources Abstracts	1968 - 1986	356
9.	NTIS (U.S. Government Sponsored Research Reports)	1964 - 1986	112
	Total Number of Citations:		1,803

Personal contacts were made with a number of people who are either known to be active in erosion research or otherwise knowledgeable about this field. A list of those who were contacted is given in Table 2. Each person was asked about the availability of current research or published information pertinent to the study objectives. These contacts led to the acquisition of some of the most recent information which has not yet been catalogued in the data bases.

Additional references were obtained from the citations in the papers themselves as well as manual searches in the MacLaren library for literature related to uranium mill tailings disposal sites. This latter source provided a "Selected Bibliography for Nuclear Facility Decommissioning and Site Remedial Actions" by P.T. Owen et al. from which a number of papers on long-term stability were obtained.

TABLE 2

LIST OF PERSONAL CONTACTS

Name	Affiliation
1. B.J. Barrfield	Kentucky Water Resources Inst., Lexington
2. Dr. Bilvardi	-
3. Terry Day	Environment Canada, Sediment Survey Section
4. Al Gorman	Queen's University, Kingston
5. J. Locat	Laval University
6. Bob Meade	USGS Denver
7. M. Nicklin	University of Nebraska, Civil Engineering
8. U.S. Nuclear Regulatory Commission (NUREG)	Washington
9. A. Rogowsky	Penn State University
10. R. Warner	University of Kentucky, Ag. Eng. Dept.

3. Results of Literature Review

The information received was organized into four categories:

i) causes and processes of gully erosion

ii) methods of quantifying the potential for gully erosion and rates of growth

iii) procedures for measuring gully erosion

iv) case histories and field data.

3.1 Causes and Processes of Gully Erosion

The causes of gully erosion are fairly well documented in the literature. It is a process of incision by concentrated runoff. The initiation and growth of gullies occurs when a stable or equilibrium condition of erosion and deposition is disturbed or exceeded. This is fundamentally related to the energy gradient (slope) of the watershed, the degree of concentration of the runoff (flow rate), the sediment content of the runoff and the erodibility of the soil. The equilibrium state is a dynamic one fluctuating between periods of erosion and deposition as conditions change over long time spans. It has also been observed that a system may gradually evolve towards an unstable condition through natural processes so that a

runoff condition that had previously been a relatively minor disturbance or stress (such as a moderate flood peak that was previously controlled) will now cause the stability threshold to be exceeded, resulting in sudden and rapid gully erosion. (See Figure 3(a)) After this sudden erosion occurs, the system may return again to a relatively stable state for some time. Thus gully erosion is usually an intermittent process.

The primary causes of gully erosion identified in the literature are:

i) increased surface runoff and/or reduced infiltration.

This may be due to changes in land use, reduced vegetation cover, climatic changes, increased drainage area (regrading, diversions of swales and channels), etc.

ii) increase in energy gradient.

This may be due to a lowering of the downstream control level (flood control works, lowering reservoirs), ground subsidence or uplift, excavations, etc.

iii) decrease in upstream sediment supply.

This may be due to changes in land use, increased vegetal cover, exposure of bedrock, etc.

iv) exposure of less resistant soil layers.

Some of these causes may be man-induced but others reflect natural geomorphic and geologic processes over long periods of time. There are also a number of specific physical parameters which are important to erosional processes:

i) climate - Precipitation is considered to be one of the principal factors in the erosion process, especially storm events which are very intense and produce large runoff volumes. However, large runoff volumes are only a problem where there is sufficient erosive energy to break through the erosion threshold of the land form. This is also a function of the drainage area.

Climates which have extremes of precipitation or temperatures tend to be more prone to erosion. Drying and cracking of surface soils followed by heavy rains leads to large runoff volumes (less infiltration) which may concentrate in the cracks and lead to gullying. Freezing may cause heaving and cracking of surface layers (particularly in engineered covers) and thawing of surface soils while underlying layers remain frozen greatly reduces the resistance to erosion.

ii) vegetation - There is a close relationship between vegetation and climate and in some climatic regimes vegetation cover may die off during periodic droughts. Forest fires are also a common occurrence in many

areas. For these reasons, vegetation cover cannot be considered as a completely secure protection against erosion.

iii) topography - Surface slope, roughness and landform shape are important factors since they are directly related to runoff concentration and velocity. However, it is the combination of runoff volume (related to drainage area and rainfall intensity), flow concentration (in rills or channels) surface slope and soil properties that determines the resistance of the landform to gullying. For example, under some conditions, steep short slopes may be resistant while long mild slopes might be susceptible to gullying.

iv) soil characteristics - Various soil properties have been identified as significant factors in the potential for erosion. In general, increased percolation and increased soil cohesiveness lead to less erosion. However, these properties tend to be present in inverse proportions in any given soil. As a result the erodibility of a particular soil in situ is difficult to determine from its physical properties alone unless it is of an extreme and homogeneous type (i.e. sand, heavy clay, etc.) One factor that was identified in the literature is that the susceptibility of a soil to piping may enhance the potential for gully formation.

Deterministic relationships between specific physical soil properties (such as bulk density, porosity, texture, Atterburg limits, etc.) and the erodibility of the soil have not been successfully defined by the work done to date.

v) other factors - The erosion process is so complex that many factors have been identified as significant in site-specific cases. These include modifications by man (road cuts, agricultural and land use practices, alteration of drainage courses, etc.), burrowing and foraging by animals, mass movement (landslides) in valley walls, and wind effects in arid climates, etc.

Research into the processes of rill and gully erosion has been conducted at Colorado State University using a laboratory rainfall erosion facility. This facility consists of a large bed of graded soil (silt/sand mixtures) with a rainfall simulator. Work done using this facility by Mosely (1972, 1974) and McLane (1978) give interesting results concerning the growth and stability of rills and gullies. Experimental data and results are presented in Figures 1 and 2 which describe relationships between drainage density and surface slope, sediment yield and slope geometry (e.g. convex vs. concave), and the effects of lowering the base level on the rate of gully advance. The conclusions of these studies were:

i) the density of rills increased with surface slope

ii) sediment yield increases with surface slope

GRAIN-SIZE DISTRIBUTION OF SILT-SAND MATERIAL USED IN THE EXPERIMENTAL STUDY.

Size	Percent*	Cumulative* Percent
>2 mm	1.17	1.17
1.001-2 mm	11.55	12.72
501-1000μ	15.96	28.68
251-500μ	17.04	45.72
126-250μ	15.38	61.10
62-125μ	12.08	73.18
< 62μ	26.82	100.00

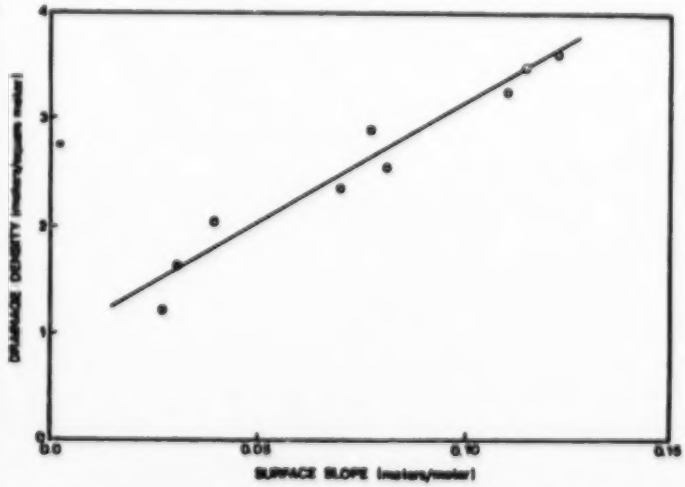
*Means of six samples

SUMMARY TABLE OF SURFACE CHARACTERISTICS.

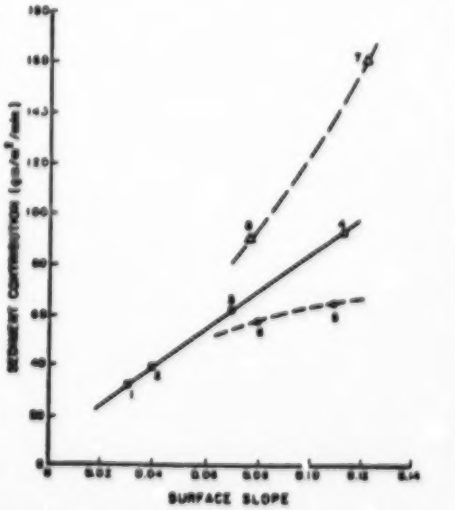
Surface no.	Shape	Contour* curvature	Gradient	Length, (meters)	Number of rills
1	plane	0.0	0.030	13.4	16
2	plane	0.0	0.039	13.4	15
3	plane	0.0	0.069	12.8	18
4	plane	0.0	0.113	8.5	16
5	divergent	25.0	0.109	5.9	20
6	divergent	25.0	0.080	5.9	16
7	convergent	-30.0	0.121	7.3	6
8	convergent	-30.0	0.076	7.3	5

*Computed by the equation (Young, 1972, p. 176): $C = \frac{0.5\,L}{\sin(\frac{\theta \cdot 180}{2})}$

in which L is a standard distance along the contour between three ranging rods, and θ is the angle subtended at the center rods by the two lateral rods.

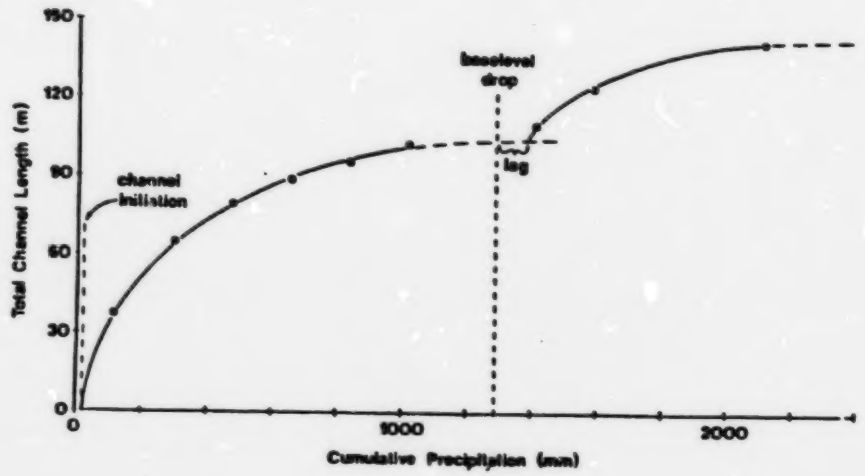


Mean drainage density as a function of surface slope (after Mosley, 1972)

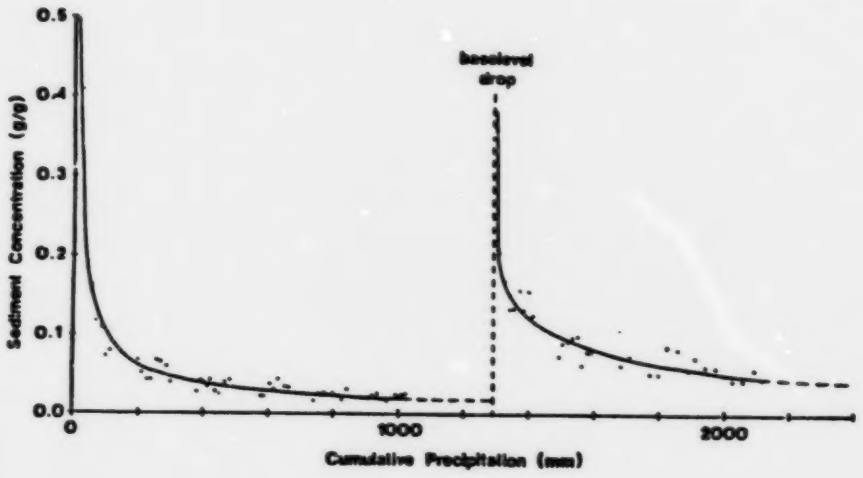


Mean sediment yield as a function of surface slope. Points 7 and 8 represent a converging surface; Points 1 to 4 represent a planar surface, Points 5 and 6 represent a diverging surface. (Mosley, 1974)

Figure 1 Experimental Results from the Rainfall Erosion Facility at Colorado State University showing the effects of surface slope on erosion.



Plot of total channel length and cumulative precipitation vs. a time index. Rapid initial increase followed by gradual slowing is evident during both growth phases. (McLane, 1978)



Plot of sediment concentration and cumulative precipitation. Exponential decrease during both growth phases reflects decrease in erosive power. (McLane, 1978)

Figure 2 Experimental Results from the Rainfall Erosion Facility at Colorado State University Showing the Effects of Lowering Base Levels on Rates of Erosion

iii) concave surfaces are more susceptible to gullying than convex surfaces

iv) the drainage pattern is largely a function of topography and it is possible to predict where channels will form from a detailed mapping of the surface

v) a lowering of the base level leads to the rapid initiation of down-cutting of the channels beginning at the down-stream face and migrating upstream

vi) the rate of head-cut advance decreases as the contributing area upstream of the head cut decreases

vii) the head-cut advance gradually ceases as a new equilibrium slope is achieved for the lower base level

3.2 Computation Methods

Most of the methods developed for numerical evaluation of gullies have dealt with the rate of growth and expansion of existing gullies in agricultural areas. These have been based on two distinct approaches. The first approach is to relate the rate of soil loss (as measured by downstream sediment loads) or the rate of gully extension (either headward advance or total area) to a number of physical parameters using regression techniques.

Among the first formulations of this type is that developed by Thompson (1964) using data from several U.S. locations:

$$R = 0.15A^{0.49}S^{0.14}P^{0.74}E1.0$$

where:

R is the rate of gully advance (ft/yr)
A is the draingage area (acres)
P is the total annual rain from events greater than 0.5 inches in 24 hours
S is the slope of the approach channel
E is the clay content of the eording soil (% by weight)

In some cases these regression formulations have become increasingly sophisticated as indicated by an equation derived for the loess soils of Iowa by Beer and Johnson (1966):

$$x_1 = 0.01\ x_4^{0.0982}\ x_6^{-0.44}\ x_8^{0.7954}\ x_{14}^{-0.2473}\ e^{-0.036x_3}$$

where:

x_1 is the gully surface area growth (acres)
x_3 is the deviation of annual precipitation from the long term average
x_4 is the index of surface runoff
x_6 is the terraced watershed area

x_8 is the initial gully length
x_{14} is the distance from gully head to watershed limit

The U.S. Soil Conservation Service (1966) simplified this procedure by reducing the basic equation to:

$$R = 1.5\ A^{0.46}\ p^{0.20}$$

where parameters are defined as by Thompson above. To account for the effect of all other factors, the USGS recommends using past gullying rates calculated from maps and aerial photos for the specific site under investigation. The equation then becomes:

$$R_2 = R_1 \left(\frac{A_2}{A_1}\right)^{0.46} \left(\frac{P_2}{P_1}\right)^{0.20}$$

in which the subscripts 1 and 2 refer to past and future respectively. This equation was developed for areas east of the Rocky Mountains and is apparently based on several years of measurements of head-cut advance on a number of gullies, although the data are not presented. A detailed knowledge of field conditions is required for a reasonable prediction using this method.

All of these regressions are limited to conditions and geographic locations similar to those for which they were developed, although they are often presented in various manuals for general application. No verification of predicted erosion rates using these methods is presented in the literature since the required time frame is too long and the erosion process too sporadic for this to be practical. For any confidence on the degree of accuracy for a specific site, especially in Canada, site-specific data are required to adapt these relationships or develop new ones.

The regression equations also require site-specific calibration and give only qualitative results. They are developed to predict soil and land area losses for agricultural purposes and they may have little general applicability to the problem of predicting potential gullying.

The second approach to estimating gully growth deals with the physical processes of gully formation and a number of deterministic procedures have been developed. These can be divided into: (i) methods of evaluating rates of active erosion (bank slumping, gully head-cut advance, channel down cutting, etc.), and (ii) methods of determining stability thresholds for gully initiation and growth. The former group is principally concerned with the design of remedial measures or the stabilization of existing problem areas. This may have some relevance if active erosion is occurring in the vicinity of a disposal site but such conditions should be avoided if possible. The main concern of this review is the initiation of growth of gullies on previously ungullied surfaces.

The state-of-the-art in the understanding of erosion thresholds is well represented in the publication entitled "Gully Erosion" by Harvey, Watson and Schumm (1985) for the U.S. Bureau of Land Management. This report summarizes the causes and processes of gully erosion and presents the results of research into predictive methods based on physical processes which are summarized below.

The concept of the stability threshold is illustrated in Figure 3(a). The slope or instability of a valley may increase gradually over time as a result of down-cutting in the receiving stream for example until it exceeds the stability threshold and gully erosion begins. The threshold may be exceeded at a lower slope due to a large runoff event. The rapid gullying has the effect of reducing the gradient once more to a stable condition and the cyclic process begins again.

The threshold parameter used in current research is the average shear stress at the soil/water interface. Using data from the semi-arid region of north-west Colorado a relationship for the Shear Stress Indicator has been developed:

$$\tau_{o(n)} = cA^{rf}S$$

where:

A is the drainage area
S is the channel slope
$\tau_{o(n)}$ is the Shear Stress Indicator for a return period flow of n years (Q_n)
r is the exponent of the runoff relationship:

$$Q_n = c_1 A^r$$

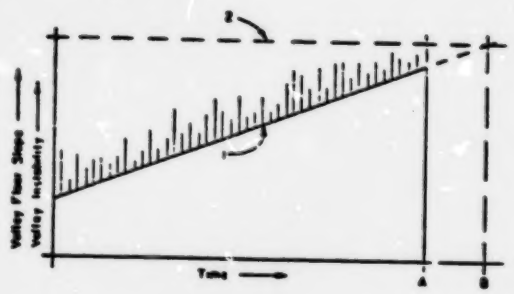
f is the exponent of the depth of flow relationship:

$$d = c_2 Q^f$$

C_1, C_2 are constants

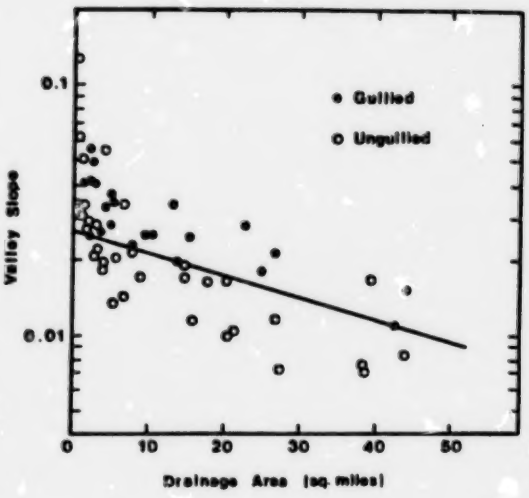
(The relationship between area, flow and return period are from earlier work by Leopold.)

From field measurements, channel slopes are plotted against drainage areas and a line is drawn through the minimum slope of gullied reaches (Figure 3b). The exponent rf is the slope of this line and a value for the Shear Stress Indicator (or threshold shear stress τ_{th}) can be calculated. This value can then be used to estimate the relative stability or gullying potential for other landforms in the region with similar soil and climatic conditions (Figure 3c). Valleys with ratios of τ_o/τ_{th} greater than 1.0 may be prone to gully erosion.



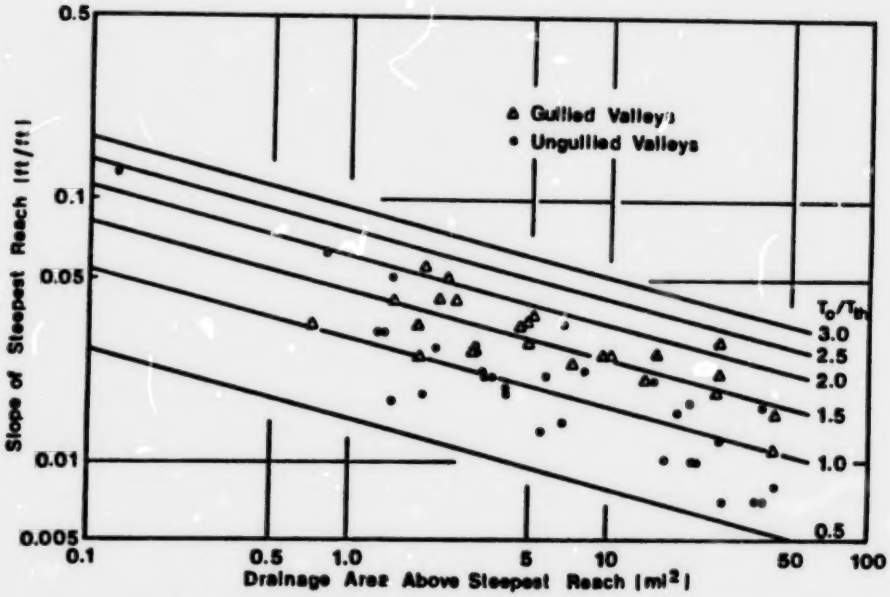
Hypothetical relation between valley-floor gradient and valley-floor instability with time. Superimposed on line 1, representing an increase of valley-floor slope, are vertical lines representing instability of the valley floor as related to flood events. When the ascending line of valley floor slope intersects line 2, representing the maximum slope at which the valley is stable, failure or trenching of the valley alluvium will occur at time B. However, failure may occur earlier, at time A as the result of a major storm or flood event. (Schumm and Hadley, 1958)

(a)



Critical valley-floor slope versus drainage area for small basins, western Colorado (from Patton and Schumm, 1975)

(b)



(c) Plot of valley-slope and drainage area showing relative shear stress indicator To/T_{th} (from Begin and Schumm, 1979)

Figure 3 Critical Shear Stress Model for Determining Gully Erosion Potential

However, it should be noted that a number of locations with Shear Stress Indicator values greater than 1.0 were in fact observed to be ungullied, mostly in small drainage areas. This would suggest that critical shear stress alone does not adequately describe gullying potential in small areas where site-specific conditions become increasingly significant. In this approach it is assumed that variations in climate, geology, vegetation, sediment and land use are minor when developing a local relationship for the critical shear stress.

The Shear Stress Indicator method has been further refined by Bradley (1980) based on data from the Chalk Bluffs area of northeastern Colorado which is essentially a bedrock surface into which channels are eroding. For these data the method was modified to consider stream power, which is the shear stress multiplied by the flow velocity, and the channel slope/width ratio. The final relationship is:

$$\tau_o V = K A_b \frac{S}{W}$$

where:

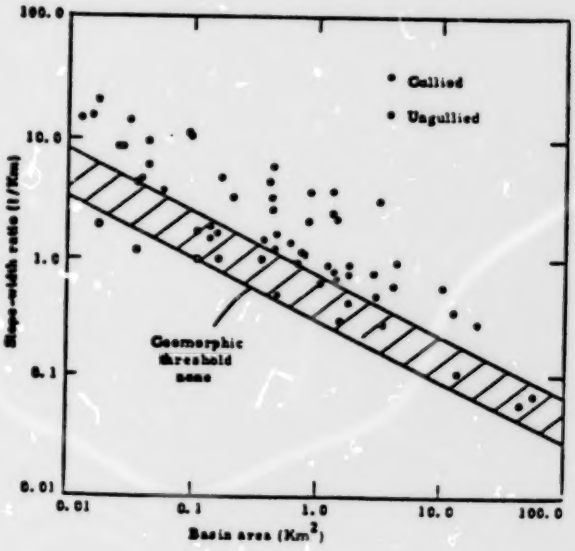
τ_o is the shear stress
V^o is the flow velocity
K is a constant
A_b is the basin area
S^b is the channel slope
W is the channel width

The constant K is determined from field data by plotting the slope/width ratio against drainage area.(Figure 4(a)). K is the slope of the line separating gullied from ungullied sites. In Figure 4(a) a geomorphic threshold zone is shown which defines the transition between gullied and ungullied conditions. The width parameter was introduced into the relationship because no well-defined threshold was apparent when slope alone was used due to the important effects of constricting valley walls at the sites studied.

Figures 4(b) and 4(c) show the use of the stream power model to define the relative gullying potential of each observed site.

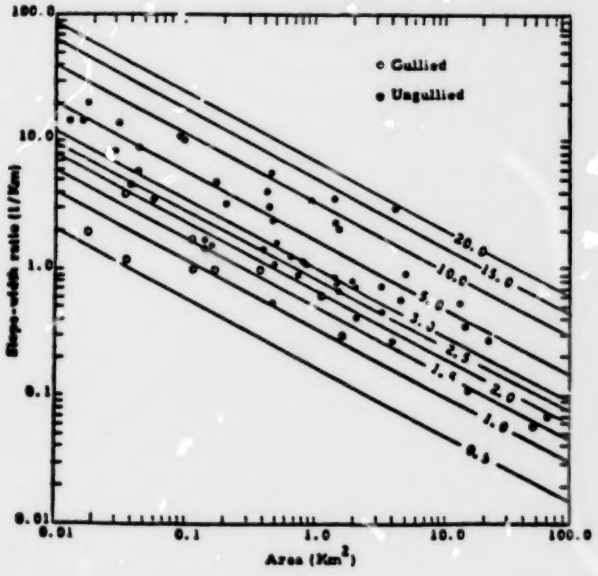
The "threshold" approach described above is not suitable for predicting the rate and extent of gullying once it occurs. For this purpose a model of erosion processes is required, based either on observed historical erosion rates, as in the regression formulae previously discussed or on measurable physical properties of the watershed.

Work at Colorado State University has lead to a deterministic method for prediction of gullying potential as described by Nelson et al. (1986). It is based on field investigations on tailings disposal sites in the arid southwestern U.S. as presented in a thesis by Falk (1985). Falk studied 16 reclaimed and abandoned uranium mine tailings disposal sites located in southern Wyoming and northern Colorado (see Figure 5). For a number of existing gullies at each location, data describing the gully dimensions, drainage area and soil characteristics were collected (see Figures 5, 6, 7a and 7b).



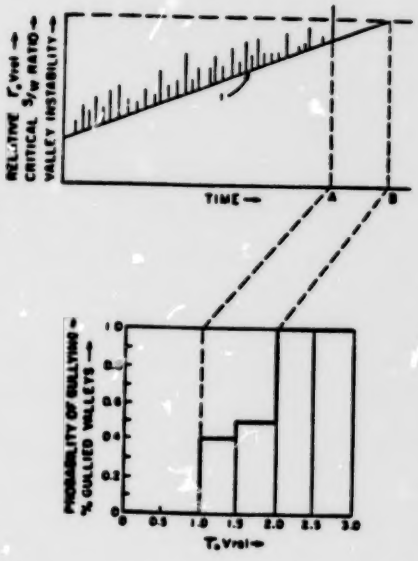
(a)

Plot of critical valley-floor slope to width ratio versus drainage basin area, illustrating the geomorphic threshold zone separating ungullied from gullied valley floors. (Bradley, 1980)



Geomorphic threshold or Stream Power Model. Lines show constant values of Relative Stream Power. Note the Geomorphic threshold zone of Figure 4-19 is between Relative Stream Powers of 1.0 and 2.0. (Bradley, 1980)

(b)



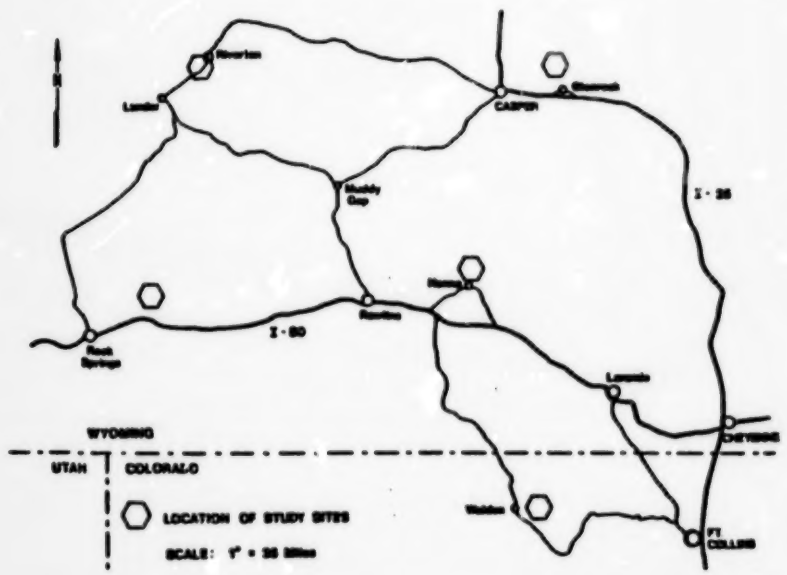
Change of valley-floor stability with time, as related to the probability of gullying for increased values of Relative Stream Power. (Bradley, 1980)

(c)

Figure 4 Critical Stream Power Model for Determining Gully Erosion Potential

Site Identification

Site	Status	Age	Origin	Location
A	Reclaimed	7	Strip-mined Overburden Rock and Soil	Casper
B	Reclaimed	11	Strip-mined Overburden Rock and Soil	Casper
C	Reclaimed	12	Strip-mined Overburden Rock and Soil	Casper
D	Abandoned	15	Strip-mined Overburden Rock and Soil	Rawlins
E	Abandoned	34	Strip-mined Overburden Rock and Soil	Rawlins
F	Reclaimed	7	Strip-mined Overburden Rock and Soil	Rawlins
G	Reclaimed	7	Strip-mined Overburden Rock and Soil	Rawlins
H	Abandoned	13	Strip-mined Overburden Rock and Soil	Rawlins
I	Reclaimed	10	Strip-mined Overburden Rock and Soil	Rawlins
J	Abandoned	10	Strip-mined Overburden Rock and Soil	Rawlins
K	Abandoned	6	Strip-mined Overburden Rock and Soil	Walden
L	Reclaimed	19	Mill Tailings	Riverton
M	Abandoned	8	Strip-mined Overburden Rock and Soil	Rock Springs
N	Reclaimed	8	Strip-mined Overburden Rock and Soil	Rock Springs
O	Reclaimed	8	Strip-mined Overburden Rock and Soil	Rock Springs
U-7	Abandoned	15	Strip-mined Overburden Rock and Soil	Rawlins



Location map indicating locations of study sites in Wyoming and Colorado

Figure 5 Locations and Descriptions of Sites for Colorado State University Studies (Falk 1985)

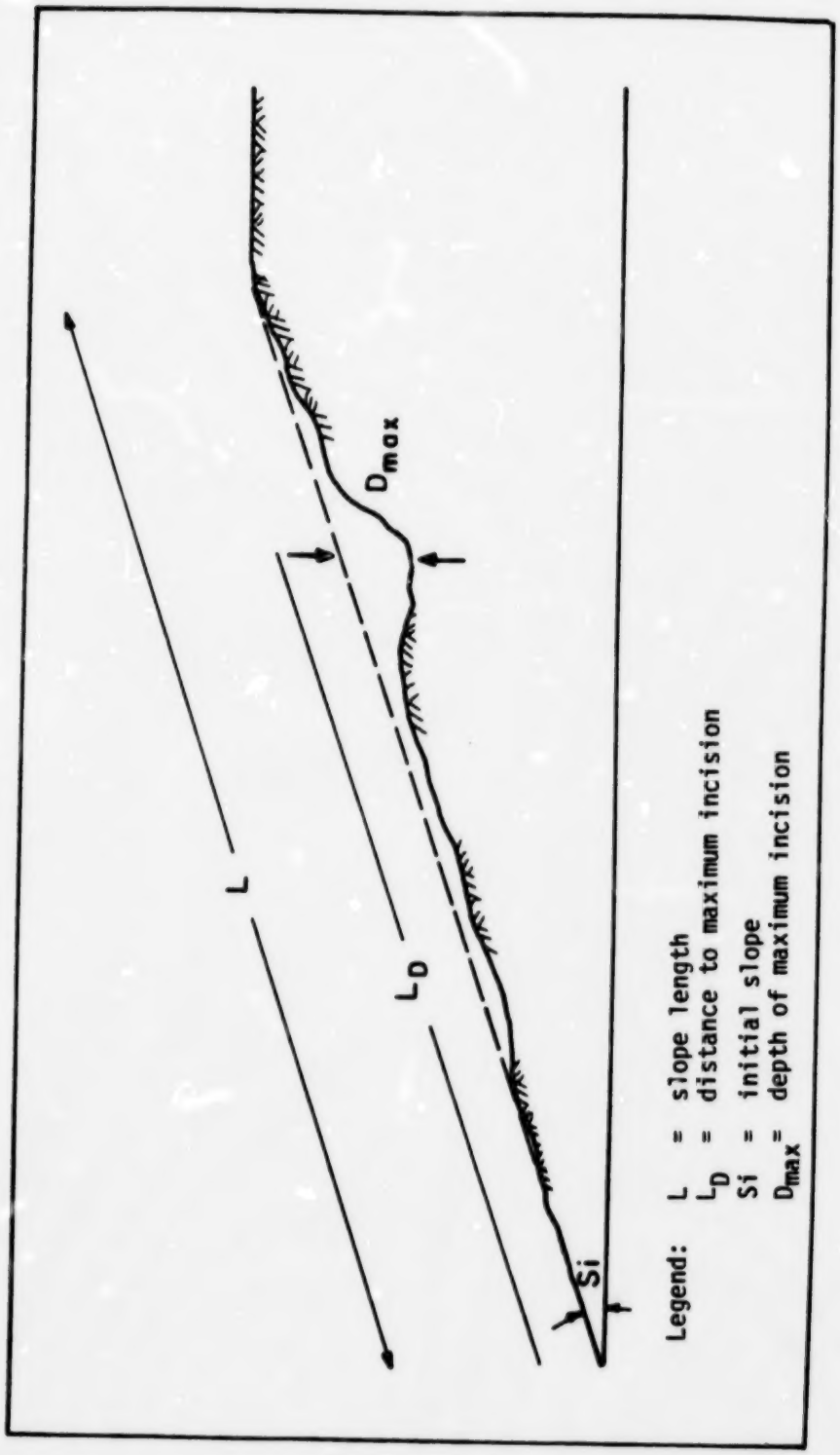


Figure 6 Lateral Cross-section of a Typical Reclaimed Slope Showing Gully and Associated Headcut (Falk, 1985)

Summary Table of Field Measurements

Site	Drainage Area (Sq Ft)	Initial Slope	Gully Length (ft)	Slope Length (ft)	Maximum Gully Depth (ft)	Width at Base (ft)	Location of Base Relative to Top	Vegetative Cover (%)
A	860	0.230	210	217	2.87	3.12	0.3013	35
B	819	0.212	301	309	1.25	2.60	0.2692	30
C	35,860	0.167	374	383	3.50	3.97	0.3970	5
D	288	0.669	344	179	1.82	2.20	0.5687	5
E	533	0.602	67	82	1.70	1.60	0.5420	30
F	4,832	0.287	203	219	1.20	2.60	0.5251	60
G	1,335	0.137	366	177	0.60	5.20	0.3164	20
H	5,176	0.399	248	262	3.17	4.27	0.1632	30
I	1,021	0.152	191	192	0.60	1.86	0.3612	10
J	2,085	0.663	222	200	2.70	3.70	0.2650	5
K	4,709	0.687	117	347	3.87	4.83	0.7936	10
L	530	0.205	49	54	2.25	5.77	0.4678	5
M	3,869	0.622	299	245	1.07	1.47	0.2779	35
N	390,000	0.166	815	826	2.90	3.60	0.9557	15
O	637	0.293	128	134	0.60	0.85	0.2510	15
D-7	15,437	0.429	203	224	4.10	4.70	0.3170	10

Summary of Laboratory Tests

Site	Percent Finer by Weight #200 Sieve	Median Grain Size (D_{50} mm)	Uniformity Coefficient (C_u)	Liquid Limit (W_L)	Plastic Limit (W_p)	Plasticity Index (PI)
A	5.9	0.36	5.77	22.4	21.3	1.1
B	2.3	0.65	6.5	28.4	19.8	8.6
C	2.7	1.00	10.00	31.8	19.7	12.1
D	---	----	----	----	----	----
E	2.5	0.36	5.22	21.4	19.9	1.5
F	0.6	0.55	5.20	30.8	23.1	7.7
G	---	----	----	----	----	----
H	3.3	2.00	10.63	29.9	23.8	6.1
I	0.3	1.74	9.42	27.8	24.0	3.8
J	2.4	0.79	13.67	22.6	21.4	1.2
K	6.7	1.82	21.25	34.2	18.7	15.5
L	0.3	0.36	2.00	20.2	----	0.0
M	0.5	0.54	9.83	22.5	21.1	1.4
N	0.4	0.46	5.69	17.9	----	0.0
O	0.2	1.60	11.05	21.0	19.1	1.9
D-7	---	----	----	----	----	----

Figure 7a Field Data and Laboratory Test Results for Colorado State Study Sites (Falk, 1985)

Grain Size Distribution of Slope Material

Percent Finer by Weight

Sieve No. / Site	4 4.75mm	10 2.0mm	30 0.60mm	50 0.30mm	100 0.15mm	200 0.075mm
A	98.4	93.1	63.2	44.4	25.6	5.9
B	95.8	86.8	44.6	26.1	12.9	2.3
C	96.7	76.9	29.9	16.9	10.9	2.7
D	No Sample					
E	94.1	84.5	56.9	37.1	21.1	2.5
F	90.9	81.5	52.2	32.5	12.1	0.6
G	No Sample					
H	76.2	51.0	21.2	11.4	6.9	3.3
I	80.3	53.7	25.6	13.0	2.6	0.3
J	87.8	70.5	44.4	30.8	21.6	2.4
K	77.6	53.4	28.3	20.1	13.0	6.7
L	99.8	99.4	92.3	28.3	4.0	0.3
M	89.8	72.7	50.8	40.6	15.2	0.5
N	95.7	78.4	53.1	42.6	7.3	0.4
O	84.6	58.3	29.2	18.3	2.9	0.2
O-7	No Sample					

Annual Number of Storm Events Greater Than or Equal to One-half Inch Precipitation (P)

Year	Casper, Wyoming	Rawlins, Wyoming	Riverton, Wyoming	Rock Springs, Wyoming	Walden, Colorado
1951	4	2	4	0	2
52	3	1	3	0	3
53	4	2	4	1	3
54	2	0	1	0	2
55	1	0	4	3	1
56	1	2	4	1	3
57	7	1	9	5	5
58	5	2	4	2	0
59	4	2	2	3	3
1960	1	1	3	0	2
61	1	1	3	2	5
62	7	2	4	5	1
63	2	4	5	6	3
64	4	0	4	1	0
65	3	4	1	6	4
66	2	1	2	2	4
67	5	0	4	2	4
68	3	2	3	4	3
69	4	5	3	3	4
1970	5	4	2	2	2
71	6	4	7	4	1
72	5	4	4	5	2
73	7	6	5	8	1
74	3	4	0	2	1
75	4	3	4	2	3
76	7	3	4	4	1
77	2	3	3	2	4
78	6	1	3	7	2
79	6	4	7	0	3
1980	2	4	4	2	3
Total	116	72	110	84	75
Average Annual Events (P)	3.9	2.4	3.7	2.8	2.5

Figure 7b Field Data and Laboratory Test Results for Colorado State Study Sites (Falk, 1985)

The rate of erosion was characterized for each site by computing the average rate of gully incision as the maximum gully depth, D max, divided by the age of the site, t.

Based on graphical correlations, the following formulation was derived:

$$\frac{Dmax}{t} = \frac{(A)(P)(Si)}{(1+D_{50})} = GF$$

where:

A is the drainage area (ft^2)
P is the number of precipitation events causing runoff
Si is the initial slope as constructed
D_{50} is the median grain size of the soil (mm)
GF is the fully factor or the average rate of gully incision.

Figure 8(a) shows the relationship between the rate of gully down-cutting D max/t and the Gully Factor GF for all sites. On this plot, reclaimed and abandoned sites are differentiated because they exhibit very different characteristics. The abandoned sites were characterized by high slope angles and a lack of vegetation while the reclaimed sites were developed to a uniform finished grade, covered with topsoil and seeded. The abandoned sites did not exhibit a good correlation between the maximum rate of incision and the Gully Factor and they were not considered further.

After eliminating the abandoned sites and modifying the data by computing average values for each site, the plot shown in Figure 8(b) was derived for the reclaimed sites only. This shows a very good correlation between the rate of incision and the Gully Factor. But this result largely reflects the relative uniformity of the reclaimed sites and the use of average values to eliminate the wide variations actually observed for all the gullies. (Figure 8(a)).

A sensitivity analysis was done to determine the relative significance of each of the terms in the Gully Factor. It was found that the drainage area is by far the most significant parameter and that the difference between using all of the terms in the Gully Factor equation and using area alone resulted in an increase in the correlation coefficient of only .051, from 0.927 to 0.978 (Figures 8(c) and 8(d). The precipitation parameter was found to be the second most important, while initial slope was the least significant.

There exists in these data an outlier shown as Point A in Figure 8. This point represents the only site in which fly ash was a component of the disposal material. It would appear that either the field sampling was not detailed enough or that the median grain size D_{50} is not an adequate parameter in the Gully Factor equation to account for this variation.

From these results the theoretical stable slope can be estimated from the curve intercept where the rate of incision is 0.0. (ie. at a Gully Factor of about 31 in Figure 8(b)).

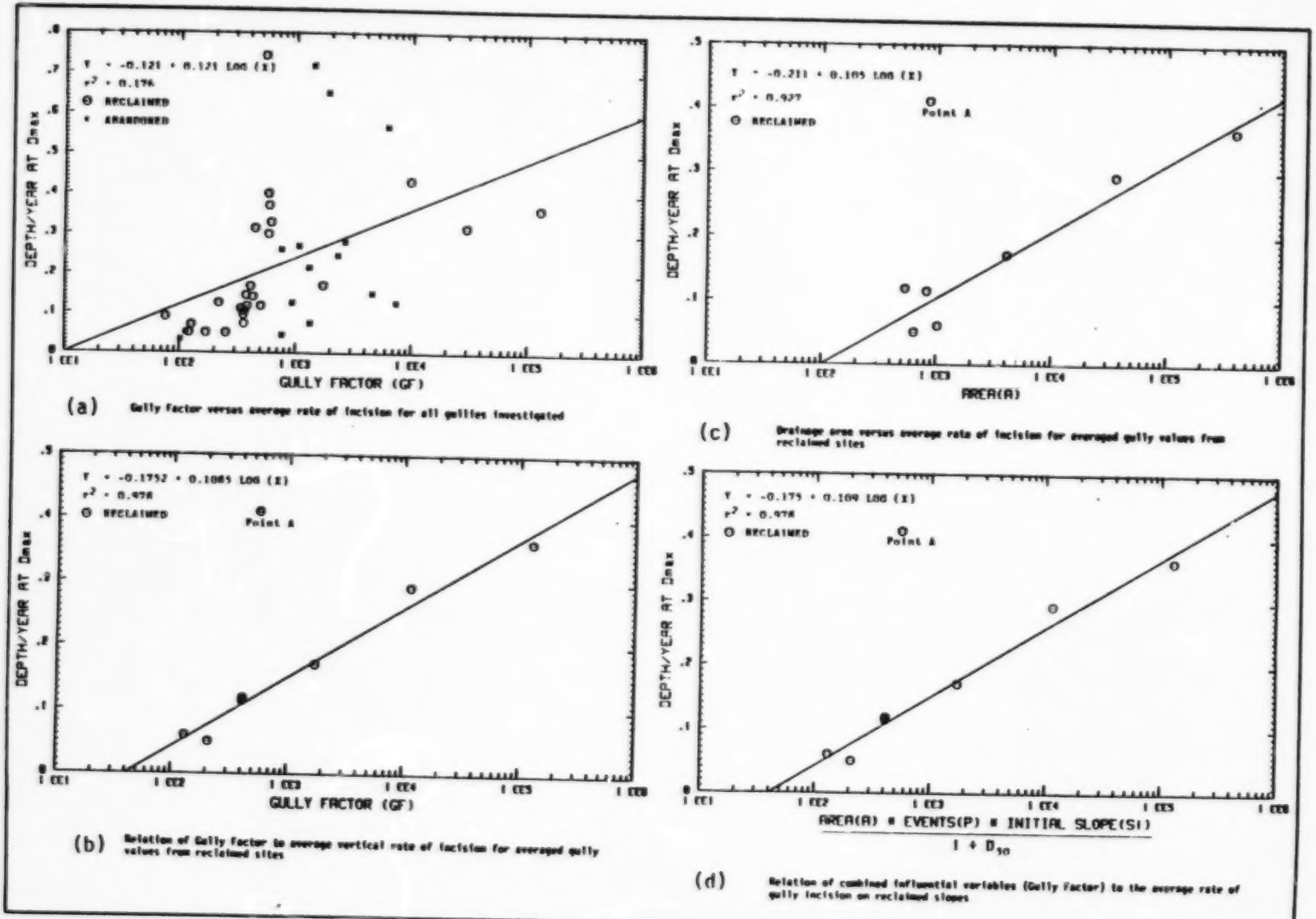

Y = -0.121 + 0.121 LOG (X)
r² = 0.176
RECLAIMED
ABANDONED
DEPTH/YEAR AT Dmax
GULLY FACTOR (GF)
(a) Gully factor versus average rate of incision for all gullies investigated
Y = -0.211 + 0.105 LOG (X)
r² = 0.927
RECLAIMED
Point A
AREA(A)
(c) Drainage area versus average rate of incision for averaged gully values from reclaimed sites
Y = -0.1752 + 0.1085 LOG (X)
r² = 0.978
RECLAIMED
Point A
GULLY FACTOR (GF)
(b) Relation of Gully Factor to average vertical rate of incision for averaged gully values from reclaimed sites
Y = -0.179 + 0.109 LOG (X)
r² = 0.978
RECLAIMED
Point A
AREA(A) * EVENTS(P) * INITIAL SLOPE(SI) / 1 + D50
(d) Relation of combined influential variables (Gully Factor) to the average rate of gully incision on reclaimed slopes

Figure 8 Results of Data Analysis for Colorado State Study Sites (Falk, 1985)

Nelson et al., (1986) presented a method to compute the critical slope or the threshold slope for initiating gully erosion on reclaimed surfaces. The method is presented below:

1. obtain site-specific information on:

   (i) cover soil (median particle diameter D_{50})
   (ii) dimensions of land fill (slope length, gradient)
   (iii) long term precipitation record.

2. define the largest tributary area for any drainage outlet. This may be estimated from the longest potential watercourse length and the following relationship:

$$D = 0.909 + 22.418\ (Si)$$

where:

D is the drainage area/unit length of drainage path (ft^2/ft) and S_i is the initial cover slope. This relationship is applied to each unique slope segment.

3. compute the stable slope gradient, S:

$$S = \frac{41.2\ (1+D_{50})}{AP}$$

where:

A is the area in ft^2,
P is the number of events/year greater than 0.5 inches in 24 hours,
D_{50} is the median particle size in mm.

If the initial slope is greater than the computed stable slope then gullying may occur. There are additional relationships presented to define the transitional slope at an interim period before the channel re-stabilizes, the maximum gully depth and maximum top width.

The assumptions behind these relationships are:

i) the method is for reclaimed slopes consisting of disturbed non-cohesive soils with mean grain sizes of 0.36 mm to 1.74 mm
ii) the reclamation material is homogeneous to the maximum gully depth
iii) the toe of the slope is stable
iv) the rate of gully erosion and slope degradation decreases with time
v) differential settlement is completed before gully formation begins
vi) vegetation cover less than 30% has negligible effect
vii) the method is based on data from the semi-arid south western U.S.
viii) the estimates of gully growth should be limited to a period of 200 years.

These results appear to be seriously limited with respect to Canadian conditions, but the methods used might be considered to develop appropriate relationships from Canadian data.

3.3 Procedures for Measuring Gully Erosion

Most gully erosion studies have involved in-situ measurements of head-cut advance, gully wall slumping and determining the rate of surface losses using marker pins and ground surveys. These data were usually supplemented by measurements of total sediment discharged in the runoff, analysis of soil properties and precipitation measurements. The limitation of these methods is that they capture only a brief period in the development of specific gullies and it is not easy to predict the future development of that gully or to generalize the results for other locations. Attempts to overcome this limitation by observing many gullies from a localized area, each taken to represent different stages of gully development within the same landform, have been only partly successful.

Photogrammetric methods have been explored to monitor the rate of soil loss and gully erosion on agricultural plots. These methods appear to be capable of measuring soil losses in the order of 10 mm to 25 mm using low level aerial photos with good ground control (Thomas et al., 1986). This approach may have some potential for inspecting remote disposal sites.

Some recent work has been undertaken to measure erosion processes on reclaimed disposal sites for uranium mill tailings from which formulae have been developed to estimate gullying potential (Nelson et al., 1986, Falk, 1985). The method was based on measuring the physical properties of existing gullies (dimensions, soils, drainage area etc.) but the resulting methods for predicting gully growth are dependent on a high degree of homogeneity between sites.

Another procedure that has been used to investigate gullying processes is a laboratory rainfall erosion facility such as the one at Colorado State University described by Mosely (1974). This facility consists of a large bed of soil that can be graded as desired and subjected to a simulated rainfall loading. Changes in base level can also be effected. Using this rainfall erosion simulation method, it may be possible to model a design for a specific reclamation site including appropriate soils, slopes, compaction, etc. It may also be possible to simulate a wide range of conditions to develop generalized relationships for design. However, such a procedure would be impractical for other types of disposal facilities (eg. underground sites with undisturbed surfaces).

3.4 Case Histories and Field Data

The literature presents summaries of many field investigations and case histories, although detailed data are rarely presented. Some examples of these are given in Table 1. Many of the studies have been concerned with the growth of existing gullies occurring either in agricultural lands or in the semi-arid lands of the American southwest.

TABLE 1

EXAMPLES OF CASE HISTORIES FROM THE LITERATURE

REFERENCE	LOCATION	CLIMATE	NATURE OF INVESTIGATION
Falk (1985)	Wyoming/ Colorado U.S.A.	Semi-arid temperate	•observations of gully erosion on 16 reclaimed and abandoned strip mines and tailings disposal sites; •site measurements, laboratory analysis of soils and rainfall data collected; •developed empirical method to predict maximum gully depth;
Stocking (1981)	Zimbabwe	Semi-arid Sub-tropical	•seven year monitoring program; •investigated correlation between many potential causitive parameters and gully growth; •developed regression equation for rate of growth.
Brumbaugh (1983)	Santa Cruz Island, California U.S.A.	Mediterranean	•hillslope gullies were surveyed on 5 watersheds with varying degrees of vegetative cover and sheep grazing and various rock types; •three gullies were monitored for 2.5 years using erosion pins and coloured stones placed in gully floors.
Piest and Bowie (1974)	Western Iowa U.S.A.	Temperate Humid	•erosion rates were measured in 4 gullies over a 10 year period; •gully changes were monitored by periodic surveys and stream floor sampling; •watersheds were in agricultural usage and ranged in size from 75 to 150 acres.
Patton and Schumm (1975)	Western Colorado U.S.A.	Semi-arid	•valley slope and drainage area were measured in 56 valleys of which 33 were stable or ungullied while 23 were gullied to some degree; •gully slope or the steepest valley section in the ungullied valleys was measured; •data used to identify critical slope for gully initiation.

The USGS (1986) has published a review of sediment data collected in mining areas of the eastern U.S. which documents rainfall runoff events monitored on many small watersheds with reclaimed areas (including one nuclear waste landfill). However, these data deal with total sediment discharges rather than gullying processes.

Recently, some investigations have been done on the initiation of erosion at reclamation and disposal sites but much of the interest is in permeability rates rather than long-term stability. The recent work done at Colorado State University on Uranium tailings disposal sites, as reported above, appears to be unique in its emphasis on gully erosion.

In general, the existing field work has been related to determining relationships between site characteristics and gullying potential and rates of growth. However, the most useful data in this regard with respect to surface and near surface disposal sites has been done in the semi-arid south west United States. Almost none of the reported field data are from cold, humid locations similar to Canadian conditions.

4. Conclusions and Evaluation

Considerable knowledge exists on the processes of gully erosion but the majority of it is qualitative and descriptive. Some attempts have been made to quantify the rate of gully advance for agricultural cases but there is little equivalent work available for reclaimed disposal sites, and none for Canadian climatic conditions. The applicability of the existing work to Canadian disposal sites has not been validated. The ability to accurately predict gully erosion in undisturbed "natural" situations appears to be beyond the present state of the art.

The major problem in predicting erosion, as gleaned from the literature, is the enormous variety of soils and conditions encountered. In this regard, there is an important difference between native soils which are highly variable and reclaimed sites which can be designed to be homogeneous and subject to more uniform and controlled conditions. The ability to control the selection and design of reclamation sites greatly improves the possibility of developing useful theoretical relationships to design for erosion protection.

Realistic estimates of erosion potential in undisturbed soils (if possible at all) must be very site-specific and dependent on detailed site investigations.

With regard to the problem of long-term stability of disposal sites, there are a number of significant gaps in the available research and technology. Based on this review of the existing literature, the following questions remain unanswered:

i) For underground sites located relatively close to the undisturbed land surface, to what degree should the long-term risk of exposure due to surface erosion be considered and how can it be evaluated?

ii) An approach has been developed to estimate the stability of reclaimed slopes to resist gullying based on field measurements and laboratory tests in the U.S. Is this approach applicable to Canadian conditions and freeze-thaw cycles in particular? Do these methods apply to the materials and construction methods available at Canadian sites?

iii) In the design of engineered covers there is a trade-off between limiting percolation and resisting erosion. These two criteria require very different soil properties and usually some form of composite or layered cover is used. What is the most effective combination of materials and general cover design to meet both of these criteria for Canadian conditions?

iv) Materials used in reclaiming disposal sites must be obtained locally. What are the minimum specifications for such materials? How should they be placed and what procedures are required for quality control during construction?

v) Each reclamation site requires a site-specific design based on local conditions. What field data and testing should be required to evaluate ultimate erosion and gullying potential?

vi) What is the most efficient and effective means of monitoring the stability of remote disposal sites over long periods of time?

vii) The long-term stability of the site depends on the maintenance of the base level at the outlet of the watershed. How can this be secured for design periods of hundreds of years?

viii)What design period is realistic for erosion protection? Is it feasible to assume that a decommissioned site will remain stable and secure in perpetuity or should some program of regular inspection and maintenance be considered?

5. Recommendations

There are many areas where research on gully erosion is required to determine appropriate design procedures for disposal sites. This research falls into two categories; basic scientific investigations of gullying processes and applications to engineering design. The scientific research areas are:

i) processes of gully initiation on reclaimed surfaces; methods to predict gully initiation on all surfaces.

ii) determination of growth rates of gullies in natural surfaces, existing valleys, engineered covers and disposal materials

iii) long term geologic and geomorphic processes with respect to potential for gullying in disposal sites

iv) methods for periodic monitoring and/or inspection of decommissioned sites

The areas requiring engineering design research are:

i) methods to prevent gully initiation

ii) reclamation and stabilization of gullies

iii) engineering design and construction procedures and risk analysis with respect to gullying potential.

To carry out this program, the work would entail field studies, laboratory experiments and office studies conducted in several stages. The central problem to be investigated is the initiation of gullies which should receive the highest priority in the first stage along with a field program of monitoring and data collection. Subsequent studies and research would build or this start by using the early results to determine the direction and priorities of further stages.
While many of the various investigations will be scientific in nature, the program should be directed towards achieving answers on policy questions and engineering design within a reasonable time frame. However, since it may take a number of years to obtain conclusive field data to verify short term results, some review and updating of the initial conclusions may be required from time to time.

The following outlines our recommendations for further research into the gully erosion question. The organization of these activities into a co-ordinated research program will depend on the required time frame, available resources and the suitability of existing field sites for study.

The recommended tasks are:

1) Conduct a field inspection of all accessible sites to identify those which may be suitable for monitoring and study. This would include any landfill or reclamation site with emphasis on locations in Canada or other sites with comparable climatic conditions. In addition, sites suitable for study of general erosion and gullying processes should also be investigated such as Casselman Landslide site.

As a result of these field inspections and a review of available Canadian data, the subsequent activities in the proposed program can be updated or modified as required.

2) Conduct a comprehensive field monitoring program at selected sites to collect data on:

i) in-situ soil characteristics
ii) drainage system characteristics
iii) precipitation and runoff measurements
iv) infiltration characteristics
v) occurrence of rills and gullies or other non-uniform erosion at or near the site

vi) rates of growth of rills and gullies
vii) stability of base level of drainage outlet
viii) rates of soil loss
ix) settlement and deformation of the site
x) vegetation cover
xi) effects of freeze/thaw cycles on erodability of soil cover
xii) effects of animal activity (burrowing or browsing)

This program will probably require several years and its continuation should be reviewed from time to time, based on the monitoring results and the results of other research activities.

3) Set-up a laboratory experimental facility to test the gully initiation thresholds for selected reclamation designs. This facility would be composed of a layered soil bed with a rainfall simulator and it should be capable of varying slopes and surface contouring. Using the simulator, experiments should be designed to investigate deterministic relationships between the measurable physical properties of various designs, erosion rates and gully erosion thresholds.

4) Since erosion experiments in the lab or the field are relatively difficult to conduct, a preliminary screening of a wide range of reclamation designs could be undertaken prior to designing the lab experiments. This screening would consider, but not necessarily be limited to, existing designs. A computer model should be developed from existing programs to simulate the processes of infiltration, runoff, and flow through the various soil layers to predict the potential for gully formation. This could be done for a wide range of soil types and layering methods to identify the gullying potential of each configuration. The results of these simulations would be used to select a reasonable number of experimental designs to be tested in the lab.

5) Based on the field monitoring, develop relationships for the rate of gully growth and advance in disposal areas.

6) Devise and test methods of stabilizing and rehabilitating existing gullies in the field.

7) Develop procedures to estimate the design life of a facility with respect to the risk of gully erosion. This would entail the consideration of the stability of the entire land form in the vicinity of the site and downstream watercourses.

8) Develop criteria regarding site selection, reclamation methods, site disturbance, slopes, site inspection, measurements, regional geologic and geomorphic data, construction and quality control.

9) Investigate the need for and methods of periodic inspection of decommissioned sites, including site inspection and remote sensing (photogrammetry). The use of stereo aerial photographs should be investigated as a means of monitoring overall site stability and performance. This should be done in conjunction with the comprehensive field program to provide detailed verification of the photo interpretations.

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